Delivering Tons to the Register: Energy Efficient Design and Operation of Residential Cooling Systems

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ABSTRACT

The work presented in this paper shows how proper air conditioning equipment location, sizing, installation and operation can improve performance, save on energy bills, and reduce peak demand. A residential heat and mass transfer model, REGCAP, was used to determine the effect of several parameters on energy consumption, peak electrical demand and air conditioner performance. These parameters included placing the entire air conditioning system within the insulated envelope of the house, reducing air conditioner capacity, correct installation (refrigerant charge and evaporator airflow), and alternative operating strategies (thermostat setback versus constant thermostat set point). Our results indicate that a properly sized and installed air conditioner has either equivalent or improved performance compared to an oversized poorly installed air conditioner that is typical of residential construction. This paper examines a recent innovation in bringing the HVAC system inside the thermal and air leakage envelope by locating the system in a cathedralized attic that is insulated and sealed at the roofline and is well connected to the house. Both field measurements and simulation results show that houses with ducts located in cathedralized attics have dramatically increased cooling performance and lower energy consumption than houses with ducts in conventional attics. However, the marginal benefit of improving an air conditioning system once it is in a cathedralized attic is small: the largest part of energy savings come from insulating and sealing the attic.

Introduction

Residential central air conditioning systems use about 11 x 10^9 kWh/year in California and are also responsible for a significant part of the peak load conditions in California and the Southwest (calculated from information given by Wenzel et al. (1997) and California Dept. of Finance (1997)). Many of the systems that contribute to this load have poor performance and high energy use.

The energy and comfort advantages of having ducts inside the conditioned space are already widely accepted by engineers. However, some architects, builders, and homeowners continue to resist interior ducts because of concerns about aesthetic, space, and construction issues. Thus, in much of the Southwestern United States, it is common practice to put ducts in attics that can reach 60°C (140°F) or even hotter (Carlson et al. 1992; Parker et al. 1997a; Walker et al. 1999).

Recently, a movement has begun to change the way that attics are built in hot and dry climates where moisture problems are not an issue (Rudd & Lstiburek 1998). The idea is to seal and insulate attic at the roof line, but not to seal and insulate between the attic and the house. This “cathedralizes” the attic, bringing it inside of the conditioned space. Such a strategy allows the ducts to be brought inside without compromising the concerns of builders, architects, and homeowners.

The main purpose of this paper is to determine the effect of cathedralized attics on air conditioner performance, energy consumption, and power demand. The effects of refrigerant charge, evaporator air flow), oversizing (relative to *ACCA Manual J*), duct leakage, and thermostat operation are considered. This work represents a continuation of air conditioner performance work reported in Walker et al. (1998) and Siegel (1999). In addition to the study of cathedralized attics, this paper adds to the previous work by including a model of air conditioner energy consumption and peak power, a more sophisticated house loads model, as well as an examination of different thermostat operating conditions.

Methods

In order to study the effects of cathedralized attics and other parameters, several simulation runs were performed with the REGCAP computer simulation program. REGCAP is designed to estimate dynamic cooling performance in houses with ducts in the attic. REGCAP links an coupled attic heat and mass (i.e. air flow) transfer model with a house heat and mass transfer model. REGCAP also includes a duct model that accounts for leakage and conduction losses as well as flow between the attic and the house when the air handler is off. A recent addition is a complete air conditioner model that models energy consumption and capacity and includes the effects of deviations from manufacturers recommended air flow and refrigerant charge (Proctor 1999). Details regarding the structure of REGCAP and required inputs are described by Siegel (1999) and Walker et al. (1998).

REGCAP Verification

REGCAP has been verified with measured data from seven different houses at a variety of weather conditions and locations (47 comparisons over all). Some of this verification work has been described elsewhere (Siegel 1999; Walker et al. 1999). More recent verification studies have focused on using REGCAP for unvented cathedralized attics. All of the verification shows a similar pattern. Specifically, the house and attic temperatures are predicted within 1°C (<3% average absolute difference in temperature for the house and <2% for the attic) over the whole day with the following caveat: if nighttime cloud cover is substantial and this data was not recorded (and consequently input into the model) that the model underpredicts attic temperature slightly (<2°C) during the night.

The duct supply and return temperatures are both predicted very closely (within 0.5°C or 4% average absolute difference from the measured temperatures) when the air handler is on, with the exception of two sites for which the predicted air conditioner capacity varies sharply from the measured values and thus affects the supply temperature prediction. When the air handler is off, REGCAP does not do as well at predicting duct temperatures, as it does not account for flows between different zones in the house or possible thermosiphon flows. This will be addressed in future versions, but does not affect the analysis for this paper because the duct system performance is dominated by the capacity of the air conditioner, not the initial temperature of the duct.

The equipment model predicts energy consumption and capacity very closely for all sites (<4% of measured capacity) with the exception of two sites that potentially had incorrect data on the nameplate or an operating problem that was not reflected in the input data. One of these simulations overpredicts capacity by about 10 %, the other underpredicts by a slightly larger amount.

The conclusion from the verification work is that REGCAP performs very well for both conventional (vented) and cathedralized (unvented) attics. Its major limitation is that it represents the attic, house, supply and return ducts each with a single zone and thus can not model intrazonal flows. This is only a limitation in such situations where such flows are important such as modeling pollutant transport or heat transfer when the air handler is off. The situation that we choose to examine in this paper is much simpler than either of these cases.

Prototype House

The prototype house that was used as the basis for the simulations for this study was a 186 m^2 (2000 ft^2) single story slab on grade house with the ducts, air handler and cooling coils located in the attic space. This house with a conventional attic was used for earlier work and is well described in Siegel (1999) and Walker et al. (1998). One important difference is that the house used in the earlier work had an asphalt shingle roof; this house has a concrete barrel tile roof.

This research also used a modified version of the prototype house: the conventional attic was replaced with a cathedralized attic. The ideal cathedralized attic is fully inside the thermal and pressure envelope of the house. It has a perfectly sealed (to outside) attic, transfer grills to allow for pressure relief between the attic and the house, and insulation at the roofline. Recent tests performed by LBNL on 4 homes with cathedralized attics in Las Vegas indicate that although well insulated at the rooflines, the attics were actually about half inside and half outside the pressure boundary of the house. There were also no transfer grills between the house and the attic. This is because the builders are in the process of changing construction methods, the procedures for sealing attics are not well developed, and the habit of sealing the attic from the house is slow to change. For this research, we simulated an attic that is in between what we saw in the field and the ideal case. The simulated cathedralized attic has twice as much leakage between the house and the attic as between the attic and the outside. This case represents an improvement over very early cathedralized attic building practices, but assumes some imperfection that is inherent in other parts of residential construction. In the end, this distinction is not as important as other effects that will be discussed in the paper. Specifically, the difference between the energy consumption of an ideally cathedralized attic and poorly cathedralized attic is only about 5%, because most of the energy savings result from the insulation location.

The following four test cases were used for both conventional attics and cathedralized attics. The parameters are summarized in Table 1. These are similar to cases used in earlier research (Walker et al. 1998) with the exception of the fact that a more thorough reading of air conditioner literature (Blasnik et al. 1996; Parker et al. 1997b) has lead us to use slightly lower air handler flows.

- **Base case** - This case describes an average new house in California. Duct Leakage numbers are based on Walker et al. (1997) and Modera and Wilcox (1995), refrigerant charge and airflow are based on average numbers from Blasnik et al. (1996) and Proctor (1997), and air conditioner sizing is based on field surveys and a contractors rule of thumb of 1 ton of air conditioner for every 500 ft^2 of floor area (Brown et al. 1994; Proctor et. al. 1995; Proctor & Albright 1996; Vieira et al. 1996).

- **Poor case** - this case describes a below-average typical house in California. Duct Leakage numbers represent the poorest quartile of measured leakage in California houses by Jump et al. (1996), refrigerant charge and airflow are based on measurements from Blasnik (1996) and Proctor (1997), and air conditioner sizing is the same as the base case. This case is bad, but certainly not the worst that exists in the region.
- **Best case** - this case describes an average new house in California that has been improved by duct sealing, refrigerant charge addition, and correction of reduced air flow. The air conditioner has not been changed as this would not typically been done in a retrofit situation. This is the best that can be reasonably achieved with a retrofit.
- **Best resized –** this is the best case with a properly sized, according to *Manual J* and *Manual S* (ACCA 1986, 1992) air conditioner.

Table 1: Prototype House Parameters

Case	Refrigerant Charge	Air Handler Flow	Duct Leakage Fraction		Rated AC Capacity
			Supply	Return	
	[%]	[m^3/hr/kW (CFM/Ton)]	[%]	[%]	[kW (Tons)]
BASE	85	167 (345)	11	11	14.1 (4)
POOR	70	167 (345)	30	30	14.1 (4)
BEST	100	193 (400)	3	3	14.1 (4)
BEST RESIZED	100	193 (400)	3	3	10.6 (3)

These four cases were examined for a conventional attic with an insulated floor and typical venting (1:300 vent area to roof area) and a cathedralized (unvented and insulated at the roofline) attic. Each of the cases were run for two different thermostat operation conditions:

- **Pulldown –** The air conditioner is turned off at 9 am and turned on at 4pm to a set point of 24°C (75°F). This simulates a common condition in California in which occupants are not home during the day, the air conditioner is turned off during that period, and is turned on to cool down the house near the time when they return home. The air conditioner actuation is often done with a programmable thermostat.
- **Continuous Cycling –** One set point of 24°C (75°F) (as used in ACCA 1996). The air conditioner cycles throughout the day to meet this set point, regardless of whether the homeowner is present. No internal gains were assumed for either scenario.

The weather that was used for this study were the design day conditions for Sacramento, CA. The input weather data is more completely described in Walker et al. (1998).

Performance and Energy Use Parameters

The parameters that serve as the basis for the comparisons between the cases described above are:

- **Pulldown Time –** is how long the air conditioner takes to cool down a house that has been heating up all day to the set point temperature of 24°C (75°F). Homeowners typically like a fast pulldown time (Kempton et al. 1992).
- **Tons at the register (TAR) –**represents the amount of useful cooling delivered to the house through the supply registers. Walker et al. (1998) report that this number is always much lower than the nameplate capacity of the air conditioner.
- **Energy Consumption –** is the total energy used by the air conditioner over the course of a day. It includes the energy consumption of the compressor, air handler blower and the condenser fan.
- **Peak Power –** is the 15 minute peak power use of the air conditioning system. Typically of little interest to homeowners (because they usually do not pay demand charges), it is of interest to utilities, particularly those which have to deal with heat storms and other "loads from hell" caused by residential air conditioners (Brown et al. 1994; Triedler and Modera 1992).

Results

The simulations were performed using REGCAP and a 1-minute time step to capture the transient response of the system. House and attic temperatures for the Base pulldown case (both conventional and cathedralized attics) are shown below in Figure 1. In the conventional case the attic gets quite hot, 47°C (117°F). This has a dramatic impact on air conditioner performance because it increases conduction losses. On peak temperature days, this would be even higher. In addition, any air entering return leaks is at this high temperature. Also note that in both cases, the attic temperature is reduced by supply leaks when the air conditioner is on. Much of this energy is lost in the conventional attic, but is recovered in the cathedralized case.

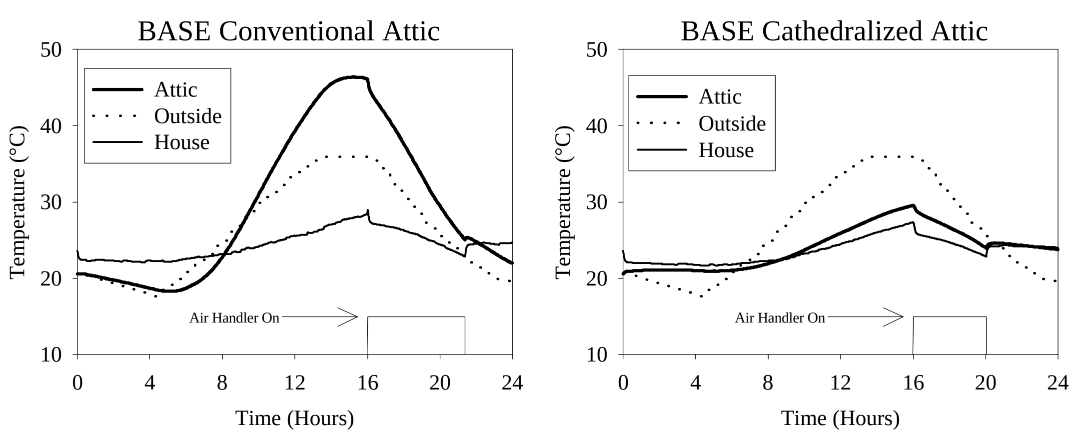

Figure 1: Temperatures for Conventional and Cathedralized Base Case Simulations

Pulldown Operation Results

To examine the impact on performance, Table 2 shows the pulldown times and the tons at the register, ranked by increasing pulldown time. The pulldown time ranged from about 100 minutes for the Best cathedralized attic case to almost six hours for the poor conventional case.

Table 2: Performance Parameters
Sorted by Increasing Pulldown Time (Faster is Better)

Case	Attic Condition	Pulldown Time [minutes]	Delivered Power "Tons at the Register (TAR)" [kW (Tons)]	Ratio of TAR to Base Case [%]	Ratio of TAR to Nameplate Capacity [%]
BEST	cathedralized	106	9.4 (2.7)	160%	67%
BEST	conventional	166	8.0 (2.3)	137%	57%
BEST RESIZED	cathedralized	175	6.9 (2.0)	118%	66%
BASE	cathedralized	179	7.5 (2.1)	127%	53%
POOR	cathedralized	196	7.9 (2.2)	134%	56%
BEST RESIZED	conventional	240	5.7 (1.6)	97%	54%
BASE	**conventional**	**266**	**5.9 (1.7)**	**100%**	**42%**
POOR	conventional	351	5.6 (1.6)	95%	40%

Pull down times are fastest for the two improved houses with oversized (4 ton) air conditioners (Best cases) and the cathedralized Best case is an hour faster than the conventional Best case. For the remaining three comparisons, including the two houses with properly sized 3 ton air conditioners (Best Resized cases), all of the cathedralized cases pulldown at least an hour faster than their conventional counterparts. This gap increases to two and a half hours for the Poor cases. Pull down times are grouped quite tightly for the cathedralized cases, but are widely spaced for the conventionally vented and insulated attics. This is shown graphically in Figure 2, which has the measured house temperatures for each of the four conventional cases and the base cathedralized case starting from a few minutes before the pulldown occurred and going until the house temperature reaches the set point. The remaining cathedralized cases have similar pulldown times to the base case and are not shown on Figure 2 for clarity. Note that the individual cases all start at different temperatures because the parameters that differentiate the cases also affect the house temperatures during the first 16 hours of the day. All of the conventional cases show a spike in the house temperature right at the beginning of the pulldown. The spike is caused by hot air in the attic and ducts which overwhelms the air conditioner capacity for the first minute or so of the cycle. Also, the thermostats were set to cycle once the house reached the set point of 24°C (75°F). To avoid cluttering Figure 2, only the temperature data until pulldown is achieved is shown.

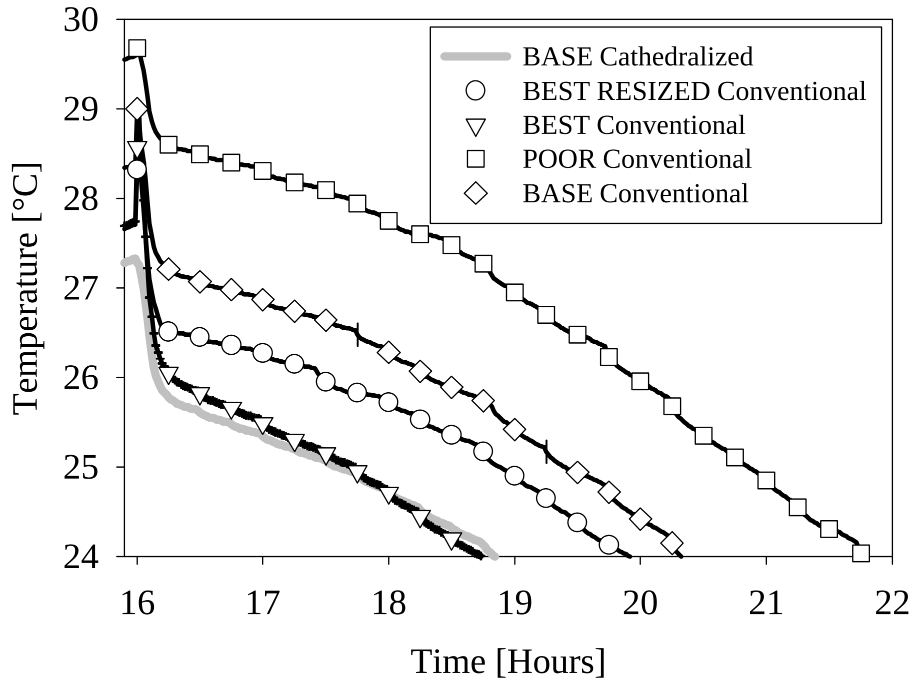

Figure 2: House Temperatures for Pulldown Cases

The tons at the register (TAR) data correspond to a fifteen minute average value from an hour after the pulldown begins to avoid initial transients. The TAR data shows similar patterns to the pulldown times. The Best cathedralized case delivers about 60 % more power to the house through the registers than the Base conventional case and the Poor conventional case delivers about 5 % less power as the Base conventional case. The Poor conventional case delivers the same amount of energy as the Best Resized conventional case even though the Poor case has a much larger air conditioner. The ranking of cases in descending TAR is different than the pulldown times because the two smaller air conditioners (the Best Resized case for both types of attics) deliver less energy to the house than the comparison Best cases because the air conditioner has less capacity (3 tons vs. 4 tons). Also, in addition to the effects of refrigerant charge and system airflow, the air conditioner capacity is a function of the inside and outside conditions. In particular, the indoor conditions vary considerably among the cases, which in turn affects the TAR.

The cathedralized attics are considerably cooler than the conventional attics (see Figure 1) which means that duct leaks and conduction losses have a much smaller effect on diminishing the tons at the register values. Even though the TAR values are typically higher for the cathedralized cases, they are an underestimate of the useful cooling delivered, because much of the energy that leaks from ducts in a cathedralized attic is recovered to the main part of the house. This energy regain, although it contributes to the cooling of the house, is not directly reflected in the TAR values, because they represent only the energy actually delivered through the registers.

The last column of Table 2 shows the ratio of tons at the register to the nameplate capacity. The results from these simulations confirm earlier work (Siegel 1999; Walker et al. 1998) that nameplate capacity is not a good indication of how much cooling an air conditioner will deliver and that duct leaks, poor refrigerant charge, and reduced air flow will lead to considerably less delivered cooling.

The pulldown times and tons at the register performance results discussed so far are also similar to the results of earlier work (Siegel 1999; Walker et al. 1998). To supplement that work, the addition of the equipment model now allows for energy consumption and peak power to be simulated. Energy consumption and peak power use for the entire system (compressor, air handler blower and condenser fan) are shown in Table 3 for the pulldown cases, and Table 4 for the continuously cycling cases. The energy consumption data for the pulldown cases is displayed graphically in Figure 3.

Table 3: Energy Consumption for Pulldown Operation
Sorted by Increasing Energy Consumption (Less is Better)

Case	Attic Condition	Daily Energy Consumption [kWh (kBTU)]	Ratio to Base Case Energy Consumption [%]	Instantaneous Peak Power [kW (kBTU/hr)]
BEST	cathedralized	13.8 (47.0)	55%	4.9 (16.8)
BEST RESIZED	cathedralized	14.4 (49.2)	58%	3.9 (13.3)
BEST	conventional	16.4 (56.0)	66%	5.3 (18.0)
BEST RESIZED	conventional	18.0 (61.5)	73%	4.2 (14.2)
BASE	cathedralized	18.2 (62.1)	73%	4.9 (16.9)
POOR	cathedralized	19.2 (65.6)	77%	5.0 (17.1)
BASE	**conventional**	**24.8 (84.7)**	**100%**	**5.4 (18.6)**
POOR	conventional	32.5 (110.8)	131%	5.8 (19.8)

Daily energy consumption values in Table 3 span a smaller range than the TAR and pulldown numbers in Table 2. Specifically, compared to the energy used by the Base conventional case, the Best cathedralized case consumes 45 % less whereas the Poor conventional case consumes 31 % more. The cathedralized cases all use less energy than their conventional counterparts and the range of energy consumption is also much smaller between the cathedralized cases, as shown in Figure 3. The energy consumed by each of the cathedralized cases varies less than between the conventional cases, because energy lost from the ducts to the attic is mostly recovered to the house.

There is one seemingly paradoxical result in Table 3. The Best Resized cases consume about 10% more energy than the Best cases even though the only difference is that the Best Resized cases have smaller air conditioner than the Best cases (3 tons vs. 4 tons). The 4 ton air conditioner has a higher flow rate through the same duct system as the resized unit (see Table 1). This leads to proportionally less conduction loss for the 4 ton unit. This effect explains almost all of the difference between the Best and the Best Resized results with very minor additional contributions from increased fan efficiency and a slightly higher energy efficiency ratio (EER) for the Best case. This result should not be interpreted to mean that a bigger air conditioner is better. Oversizing an air conditioner can have significant negative impacts on the ability of a system to control humidity.

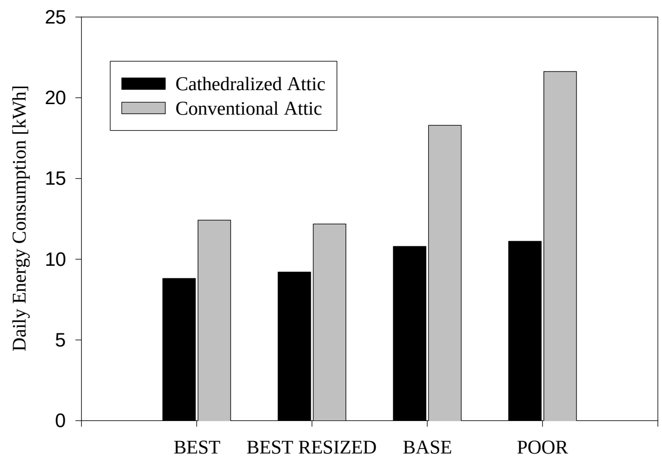

Figure 3: Cathedralized vs. Vented attic Energy Consumption for Pulldown Operation

The energy consumption data for the conventional simulations show that leaky ducts in a hot attic, reduced airflow and low refrigerant charge have a profound impact on energy use. Correcting these problems from the Poor conventional case to the Best conventional case leads to a 42% decrease in energy use.

From the perspective of a homeowner who operates her system in a pulldown manner it is clear that the Best cathedralized case is the most desirable. Compared to the Best Resized cathedralized case, it uses slightly less energy and the pulldown is considerably shorter. The pulldown is faster for the Best case because it has a larger air conditioner. However there are two disincentives to having an oversized air conditioner. The first is that the capital of an extra ton of air conditioning is approximately $500, which is ultimately paid by the homeowner. The second is that the additional peak power load is a cost to the electric utility. The smaller air conditioner has a 20-25% reduced load. Furthermore when operated in a continuous cycling manner (such as on the weekends) in a hot humid climate, the significantly oversized air conditioner may not provide sufficient dehumidification for occupant comfort.

Continuous Cycling Results

Table 4 shows the energy consumption for the continuously cycling cases. The energy consumption for these cases is larger than the energy consumption for the pulldown operation cases, because the house is kept cooler for more of the day than for the pulldown case, particularly when it is hot outside. With continuous cycling, the houses with cathedralized attics all consume less energy than their counterparts with conventional attics. They also consume less energy relative to the base case than for the pulldown operation cases discussed above.

Although the data in Table 4 indicate the energy consumption benefits of cathedralized attics there is also an important comfort benefit. The air conditioning systems in the cathedralized cases are better able to maintain a constant and comfortable air temperature in the house because they ultimately lose less cooling energy. The Poor conventional case went above 25°C (77°F) twice over the course of day because the load on the house was greater than the cooling delivered to the house.

Table 4: Energy Consumption for Cycling Operation
Sorted by Increasing Energy Consumption

Case	Attic Condition	Daily Energy Consumption [kWh (kBTU)]	Ratio to Base Case Energy Consumption [%]	Instantaneous Peak Power [kW (kBTU/hr)]
BEST	cathedralized	16.6 (56.5)	43%	4.8 (16.4)
BEST RESIZED	cathedralized	17.6 (60.2)	45%	3.8 (12.8)
BASE	cathedralized	22.2 (75.7)	57%	4.7 (16.1)
POOR	cathedralized	22.7 (77.4)	58%	4.7 (16.2)
BEST	conventional	24.0 (81.9)	62%	4.8 (16.3)
BEST RESIZED	conventional	25.9 (88.4)	67%	3.8 (13.0)
BASE	**conventional**	**38.8 (132.3)**	**100%**	**4.8 (16.5)**
POOR	conventional	53.5 (182.6)	138%	5.0 (17.1)

Conclusions

Our results indicate that cathedralizing (sealing the attic and insulating the roof) is a practical way to improve air conditioner performance in the hot dry climate typical of California and the southwestern United States. Although it is not as efficient as actually having ducts fully in the interior space, it overcomes some of the aesthetic and construction concerns associated with interior ducts. This improvement is even apparent for “poor” systems because most of the energy losses to a cathedralized attic are ultimately recovered. The energy performance for systems in cathedralized attics is a weaker function of cooling system installation problems (excess duct leakage, insufficient insulation, low coil air flow and refrigerant charge) that make installations in conventional attics consume more energy. Compared to conventional attics, cathedralized attics also require lower energy consumption for both continuously cycling and pulldown operating conditions. When operated in a continuous cycling mode (i.e. with a constant thermostat set point of 24°C (75°)), a poor system in a cathedralized attic will use slightly less energy than a fully retrofitted and properly operating system in a conventional attic.

For conventional attics, pulldown time, energy consumption and peak demand improve dramatically when refrigerant charge, reduced air flow, and duct leakage are corrected. A larger capacity air conditioner will, of course, cool down a house more quickly than a properly sized air conditioner. However, bigger air conditioners have higher peak energy use, as well as increased first cost. Also, when using oversized air-conditioners, the performance improvements are quite modest, especially when compared to those that result from moving the duct system into a cathedralized attic. Although energy consumption is moderately improved by sealing excessive leakage in a vented attic, real energy benefits come from also correcting refrigerant charge and improving air flow. These results hold for continuous cycling operation as well as pulldown operation.

The ultimate decision about whether to achieve energy savings and performance improvements in homes by cathedralizing the attic or improving the air conditioner and ducts will likely come down to one of cost. It is hoped that this study will aid decision making by presenting the quantitative benefits of different improvement strategies.

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